Updated observational constraints on quintessence dark energy models

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Why does the Universe accelerate? Exhaustive study and challenge for the future
Symposium at Tohoku University, 10-12 Feb 2018

- GW170817 favors simplest DE models

Quintessence

For a review see S.Tsujikawa (2013)

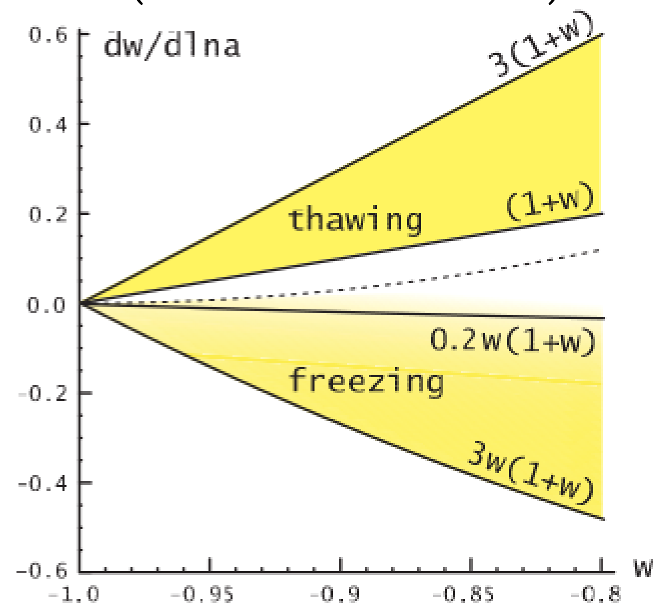
- Minimally coupled scalar field $S = \int d^4x\sqrt{-g}\left[\frac{M_{\rm pl}^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + S_m$

Quintessence models can be classified depending on evolution of

$$w \equiv \frac{P_\phi}{\rho_\phi} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}$$

→ Two classes: Freezing & Thawing

(Caldwell & Linder 2005)



- Here we consider approximate analytic w(a) for models:
  1) Tracking Freezing
  2) Scaling Freezing
  3) Thawing

and put observational constraints on the parameters in w(a)

- This analysis covers most quintessence potentials

Method

We consider the same approach as T.Chiba, A.De Felice, S.Tsujikawa (2013)

But:

- we use the Boltzmann code CLASS & MonteCarlo code MontePython
- with the latest data:
  - Planck 2015: Temperature and Polarization TT, TE & EE
  - Planck 2015: Lensing
  - Supernovae : SDSS-II/SNLS3 Joint Light-curve Analysis (JLA)
  - BAO : SDSS7 MGS, 6dFGS, BOSS LOWZ, BOSS CMASS
- we let H_0 vary (important given the current tension on its precise value…)
- and considered neutrinos

Note:

- For Quintessence we have the prior $w \geq -1$
- But we also extend the analysis to any value

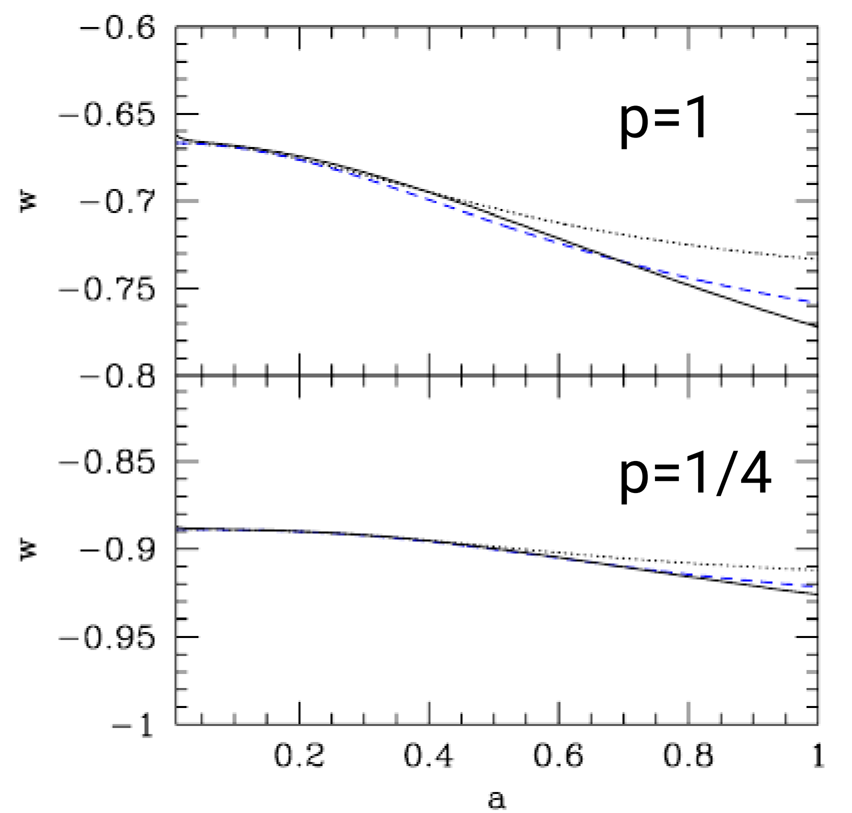
(e.g. Dutta, Saridakis, Scherrer 2009
Chiba, Dutta, Scherrer 2009)

1) Tracking Freezing models

- Inverse power-law potential $V(\phi) = M^{4+p}\phi^{-p} \quad (p > 0)$ (e.g. Binetruy 1999)

- EoS: $$w(a) = w_{(0)} + \alpha_1 \Omega_\phi(a) + \alpha_2 \Omega_\phi(a)^2 + \alpha_3 \Omega_\phi(a)^3$$

Chiba 2010



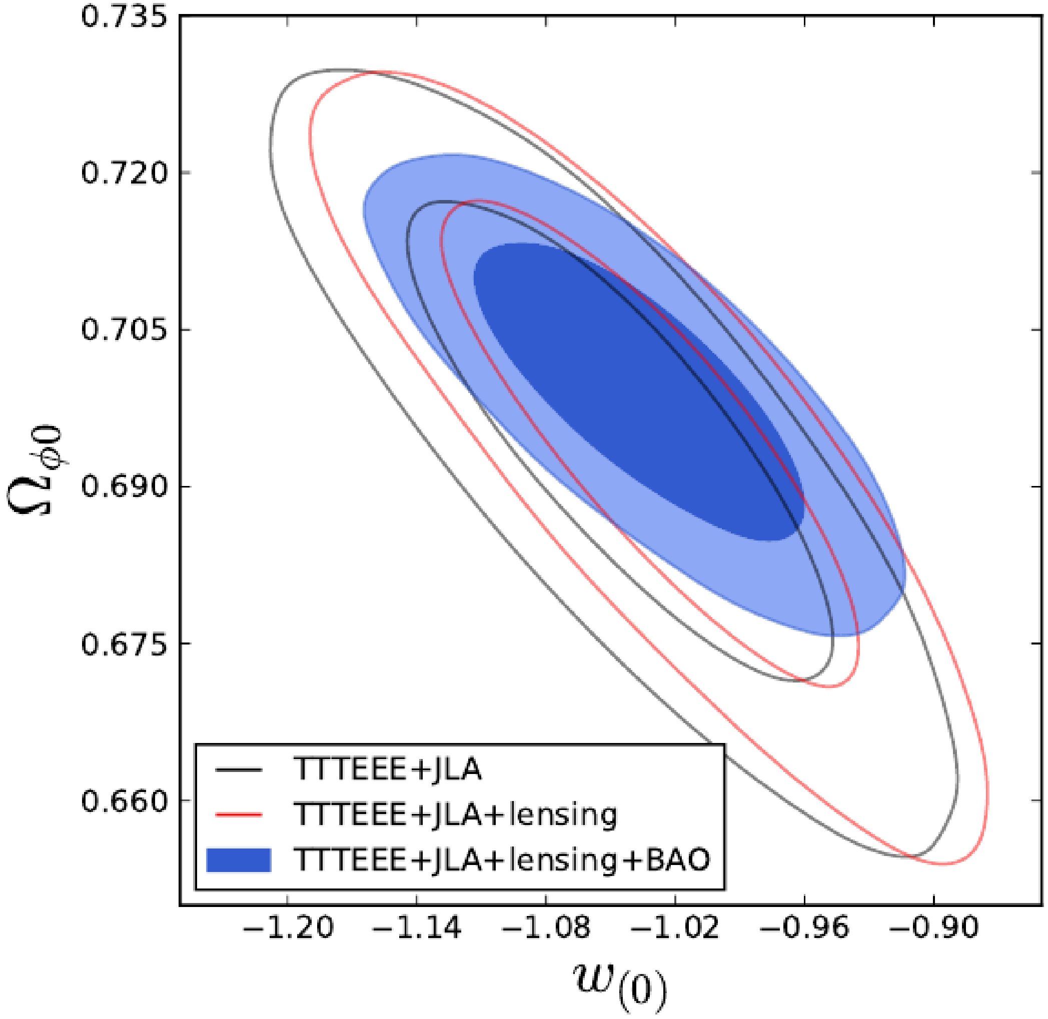
where $$\Omega_\phi(a) = \frac{\Omega_{\phi 0} a^{-3w_{(0)}}}{\Omega_{\phi 0} a^{-3w_{(0)}} + 1 - \Omega_{\phi 0}}$$

and

$$\left\{ \begin{aligned} \alpha_1 &= \frac{(1-w_{(0)}^2)w_{(0)}}{1-2w_{(0)}+4w_{(0)}^2} \\ \alpha_2 &= \frac{(1-w_{(0)}^2)w_{(0)}^2(8w_{(0)}-1)}{(1-2w_{(0)}+4w_{(0)}^2)(1-3w_{(0)}+12w_{(0)}^2)} \\ \alpha_3 &= \frac{2(1-w_{(0)}^2)w_{(0)}^3(4w_{(0)}-1)(18w_{(0)}+1)}{(1-2w_{(0)}+4w_{(0)}^2)(1-3w_{(0)}+12w_{(0)}^2)(1-4w_{(0)}+24w_{(0)}^2)} \end{aligned} \right.$$

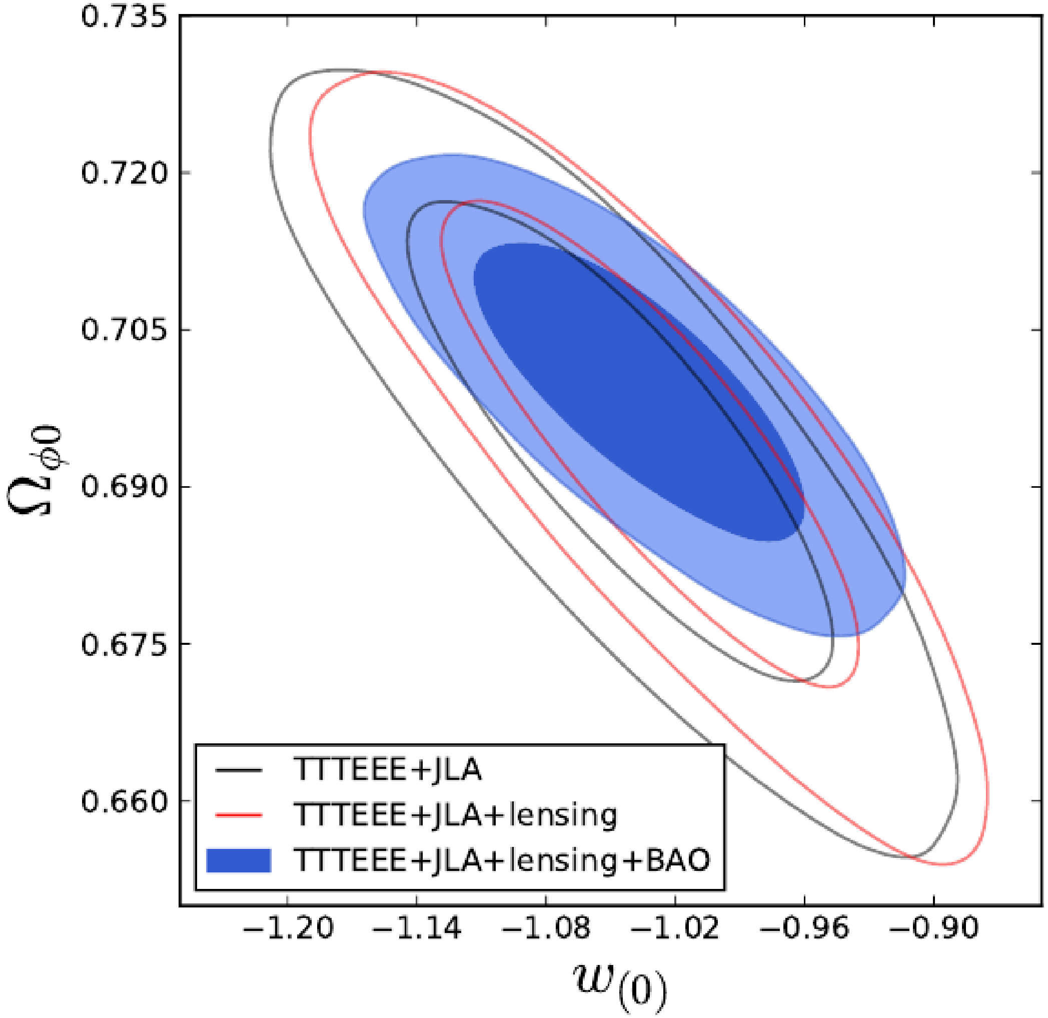
→ Two parameters: $w_{(0)}$ and $\Omega_{\phi 0}$

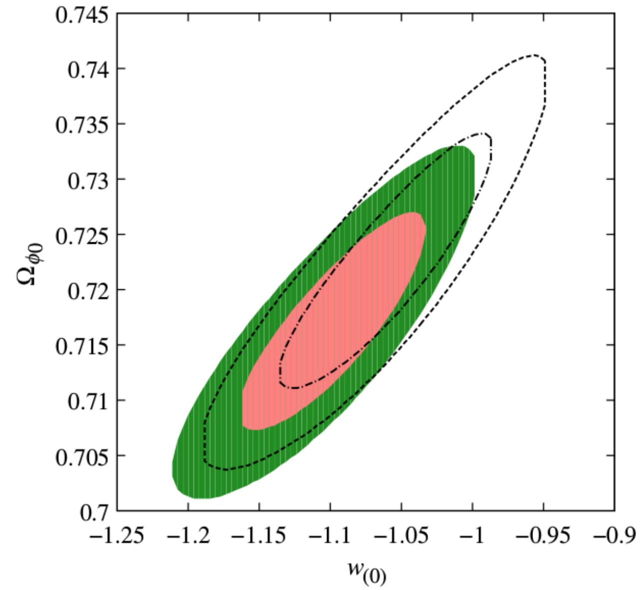
1) Tracking Freezing models



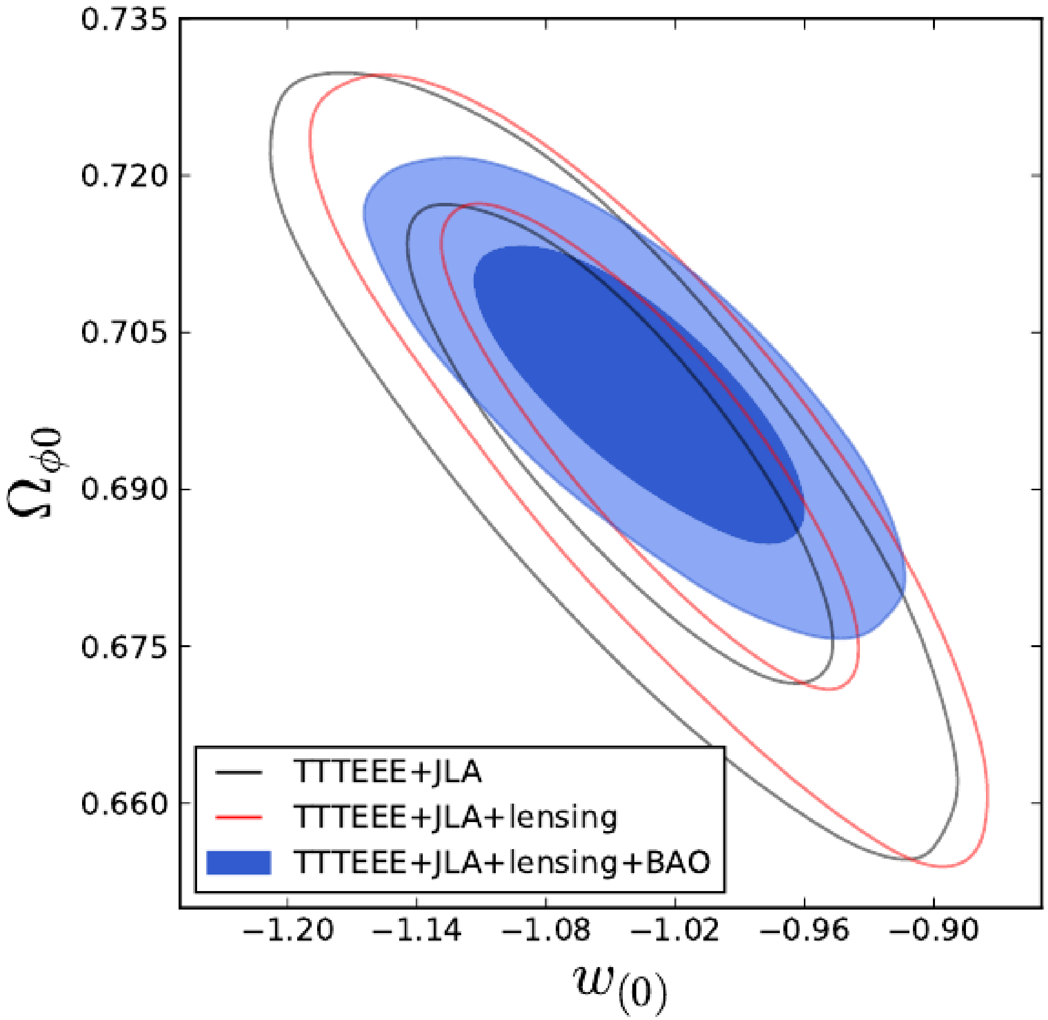
1) Tracking Freezing models

Note: Chiba et al 2013 obtained

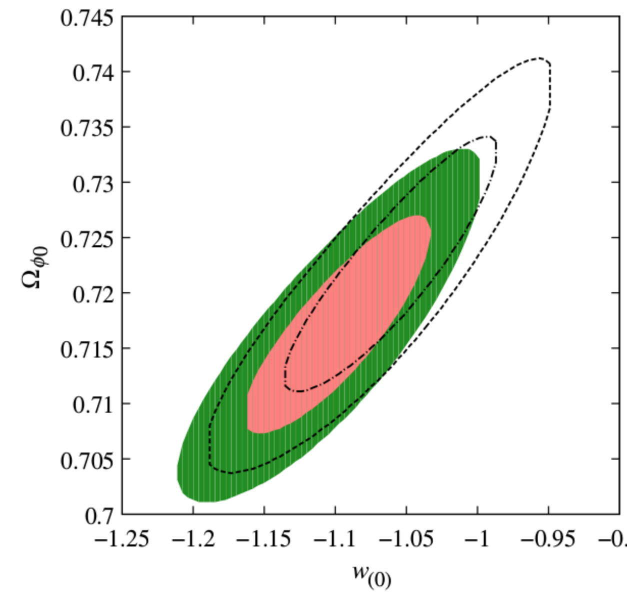




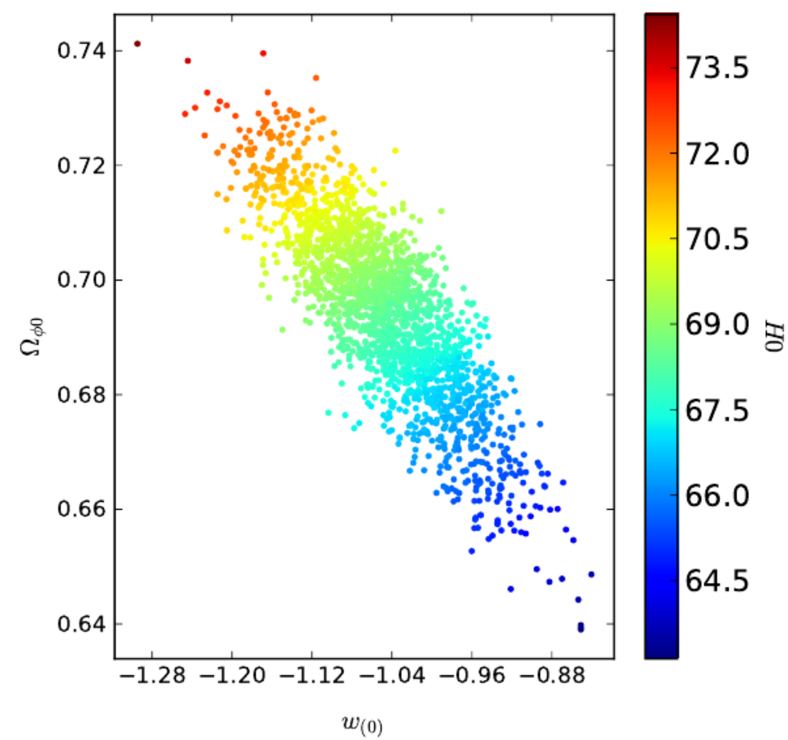
1) Tracking Freezing models



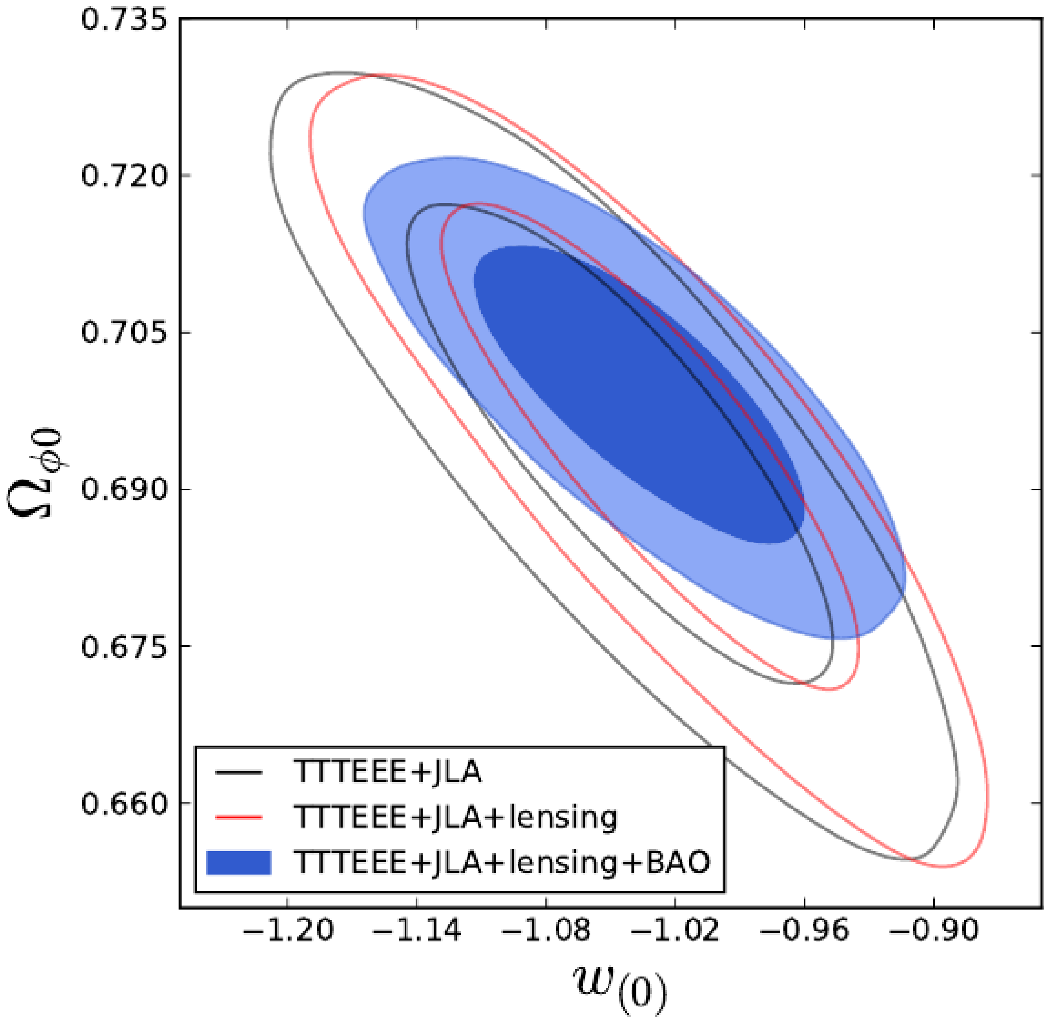
Note: Chiba et al 2013 obtained



Difference = because we let H_0 vary



1) Tracking Freezing models



Constraints: (95% C.L.)

With prior: $0.675 < \Omega_{\phi 0} < 0.703$

$-1 < w_{(0)} < -0.923$

(corresponds to $p < 0.17$)

No prior: $0.680 < \Omega_{\phi 0} < 0.718$

$-1.141 < w_{(0)} < -0.933$

2) Scaling Freezing models

- Double exponential potential: $V(\phi) = V_1 e^{-\lambda_1 \phi / M_{\rm pl}} + V_2 e^{-\lambda_2 \phi / M_{\rm pl}}$

  with $\lambda_1 \gg 1$ and $\lambda_2 \ll 1$

  (e.g. Barreiro et al 2000)

  Equation of state:

  (Linder & Huterer 2005)

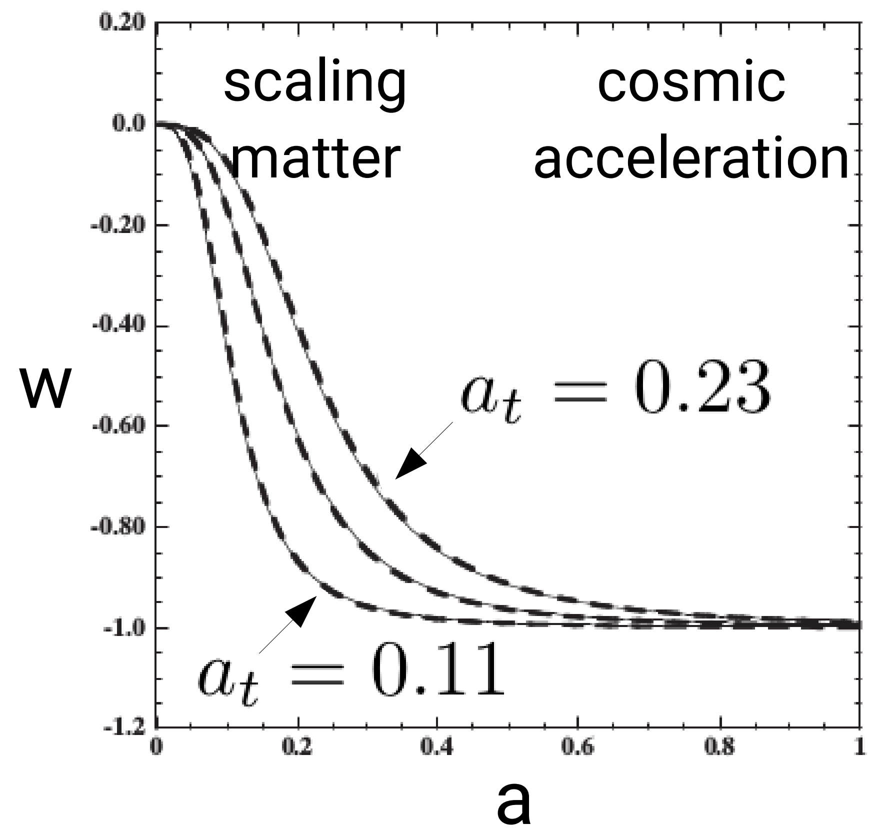
$$w(a) = -1 + \frac{1}{1+(a/a_t)^{1/\tau}}$$

with

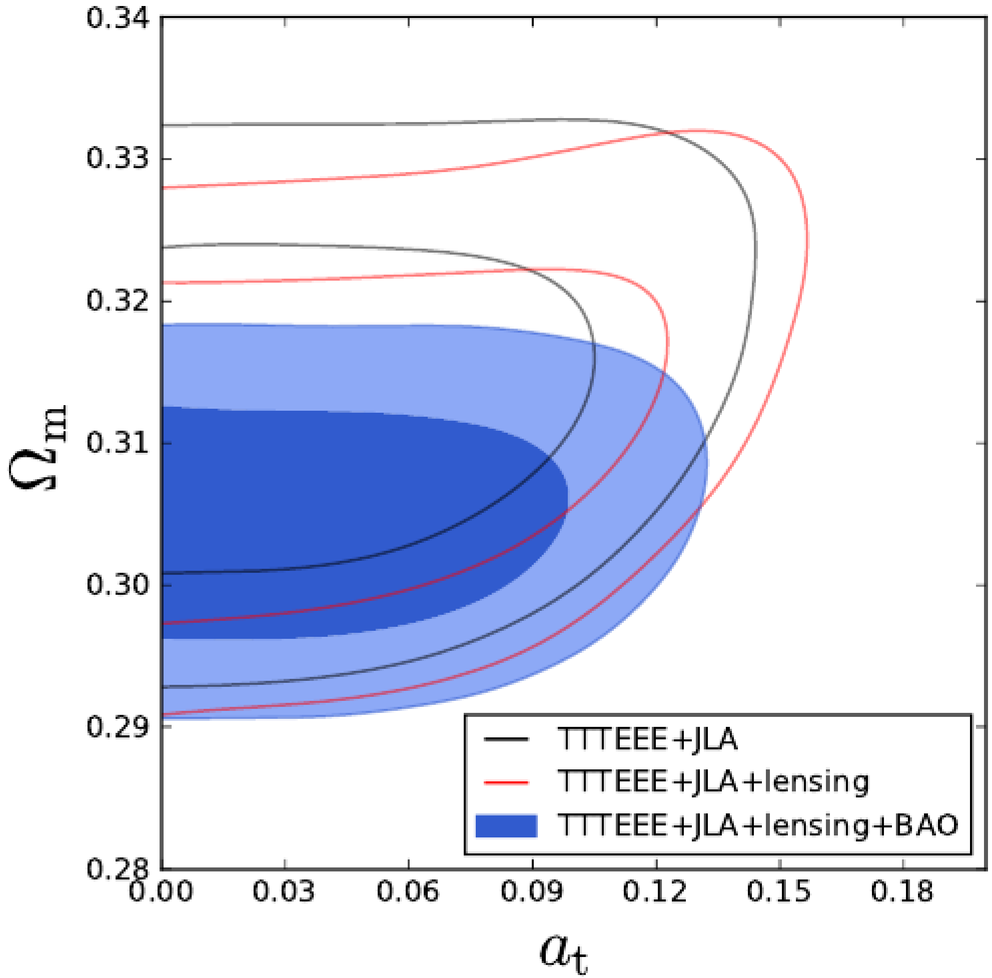
a_t scale factor at transition

$\tau \simeq 0.33$ thickness of transition

→ Two parameters: a_t and Ω_{m0}



2) Scaling Freezing models



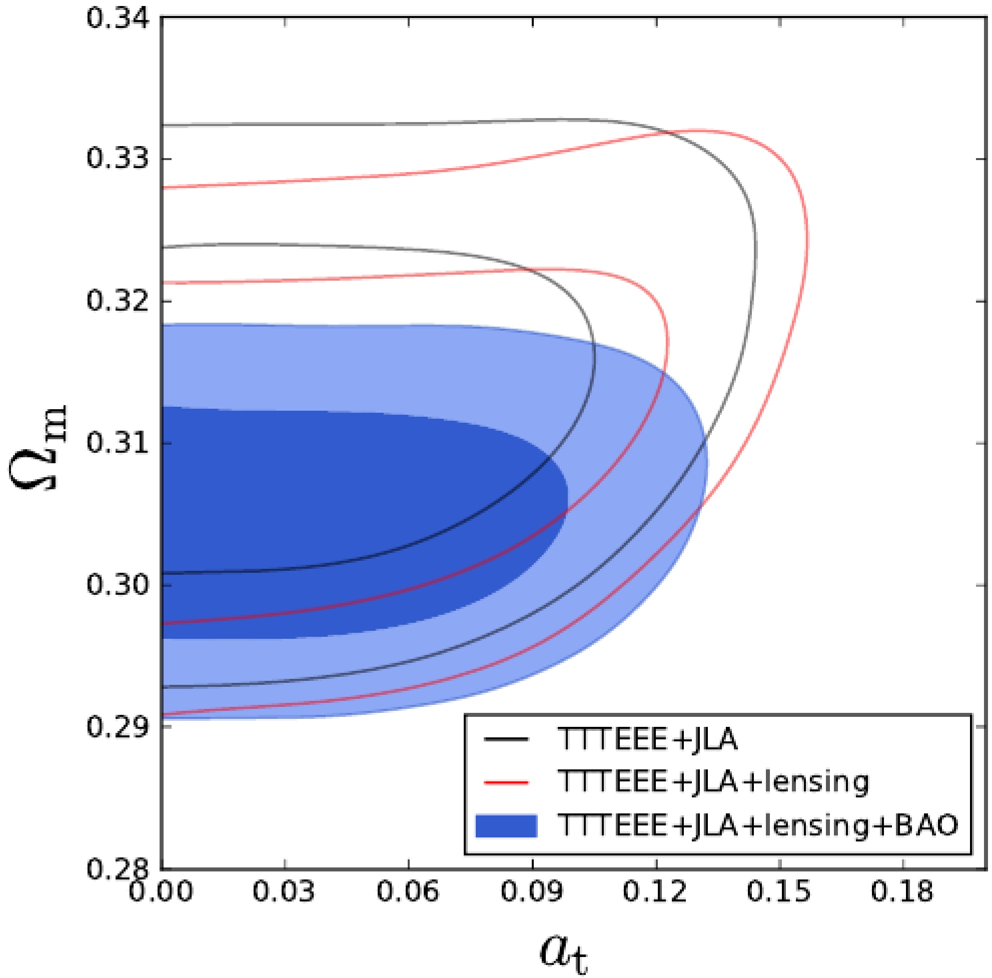
Constraint : (95% C.L.)

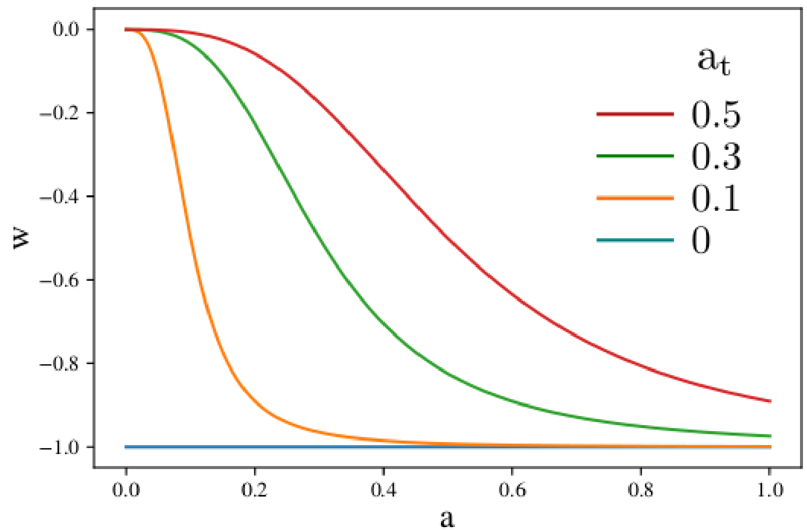
$$a_t < 0.11 \text{ i.e. } z_t > 8.1$$

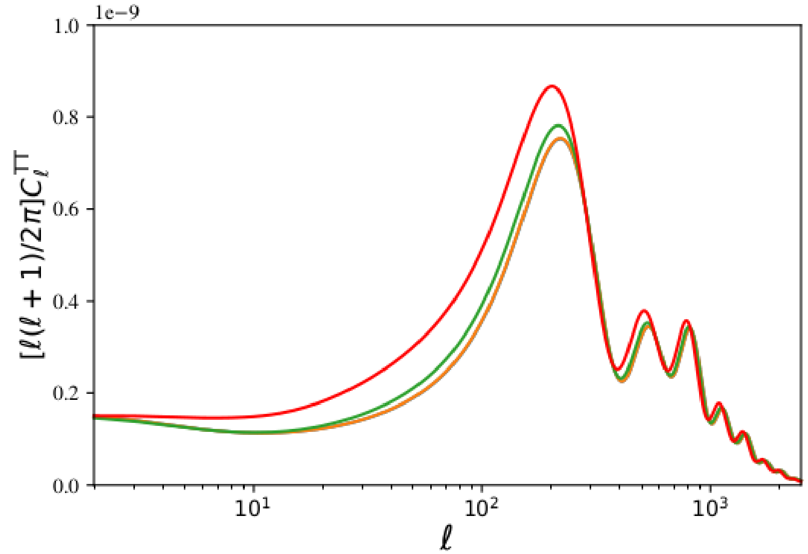
Transition to EoS close to w = -1 needs to occur at a very early cosmological epoch

2) Scaling Freezing models

Interpretation:
Large a_t → early ISW effect







3) Thawing models

- Hilltop potential: $V(\phi) = \Lambda^4[1 + \cos(\phi/f)]$ (e.g. pseudo-Nambu-Goldstone boson or axions)

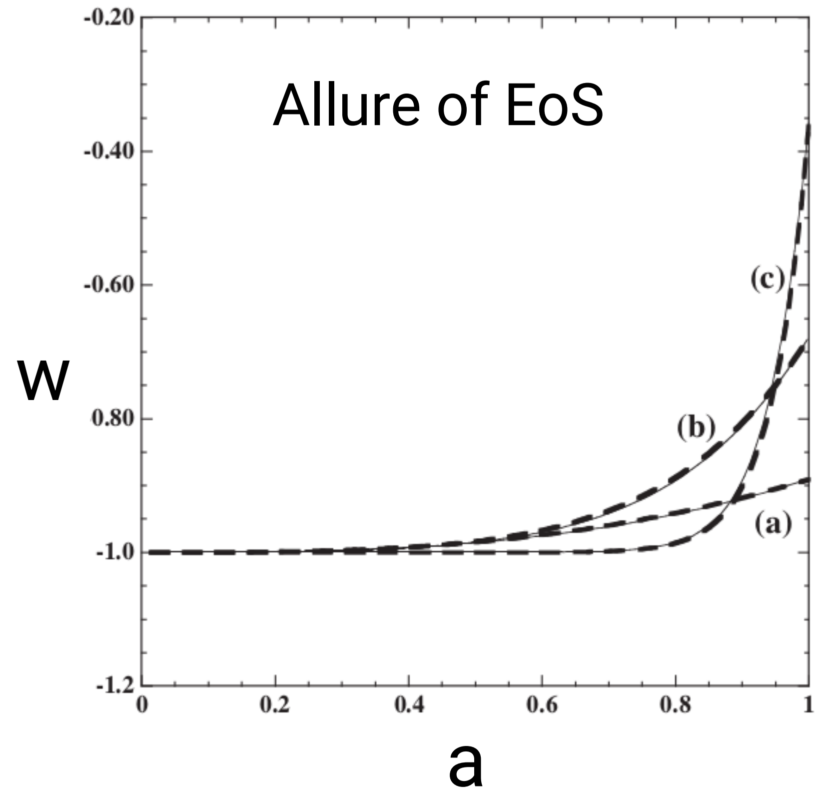
- EoS: (Chiba 2009)

$$w(a) = -1 + (1 + w_0)a^{3(K-1)}\left[\frac{(K - F(a))(F(a) + 1)^K + (K + F(a))(F(a) - 1)^K}{(K - \Omega_{\phi 0}^{-1/2})(\Omega_{\phi 0}^{-1/2} + 1)^K + (K + \Omega_{\phi 0}^{-1/2})(\Omega_{\phi 0}^{-1/2} - 1)^K}\right]^2$$

where $F(a) = \sqrt{1 + (\Omega_{\phi 0}^{-1} - 1)a^{-3}}$

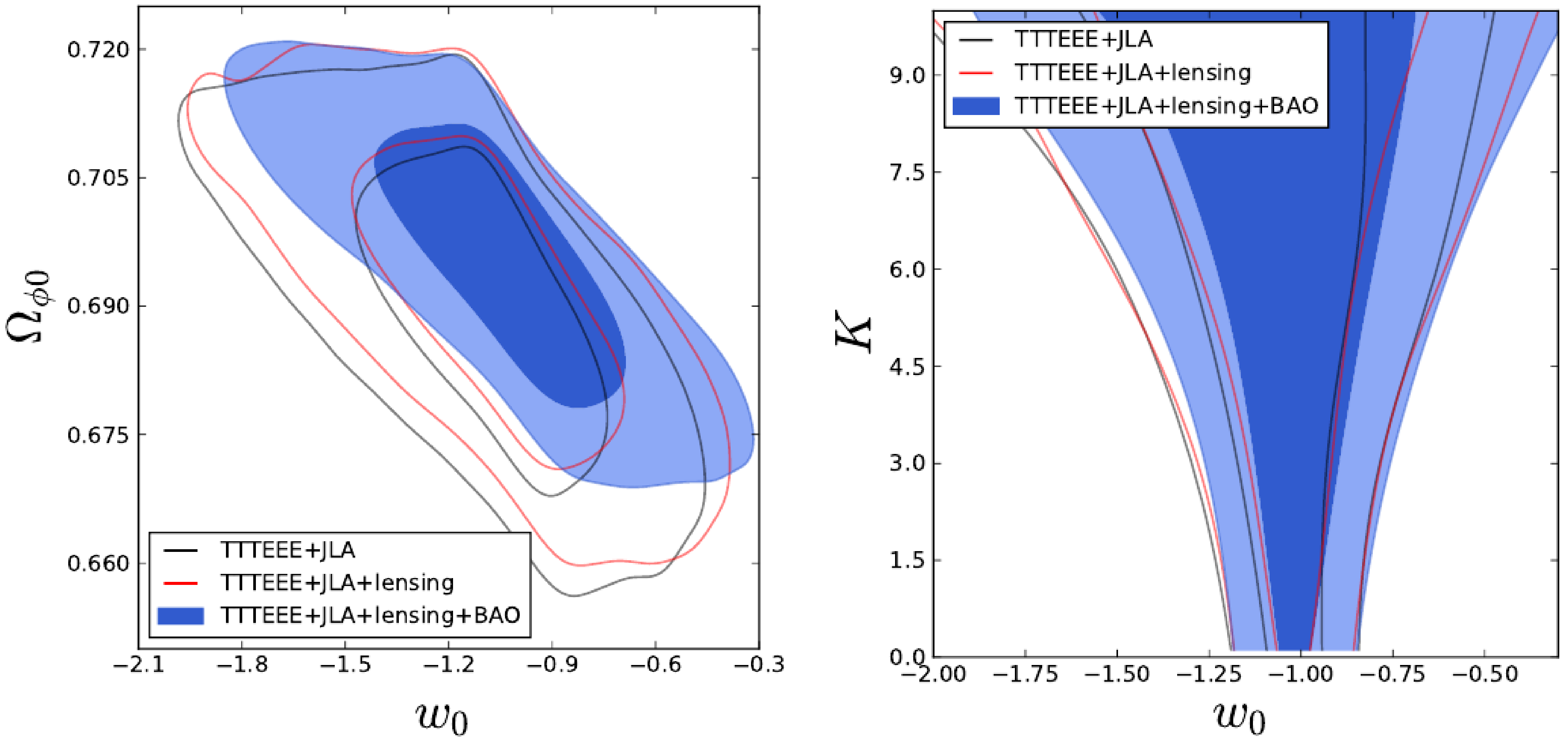
and $K = \sqrt{1 - \frac{4M_{pl}^2 V_{,\phi\phi}(\phi_i)}{3V(\phi_i)}}$

→ Three parameters: w_0, $\Omega_{\phi 0}$ and K



- Constraints with prior $0.1 < K < 10$ for approximate w(a) to be reliable

3) Thawing models



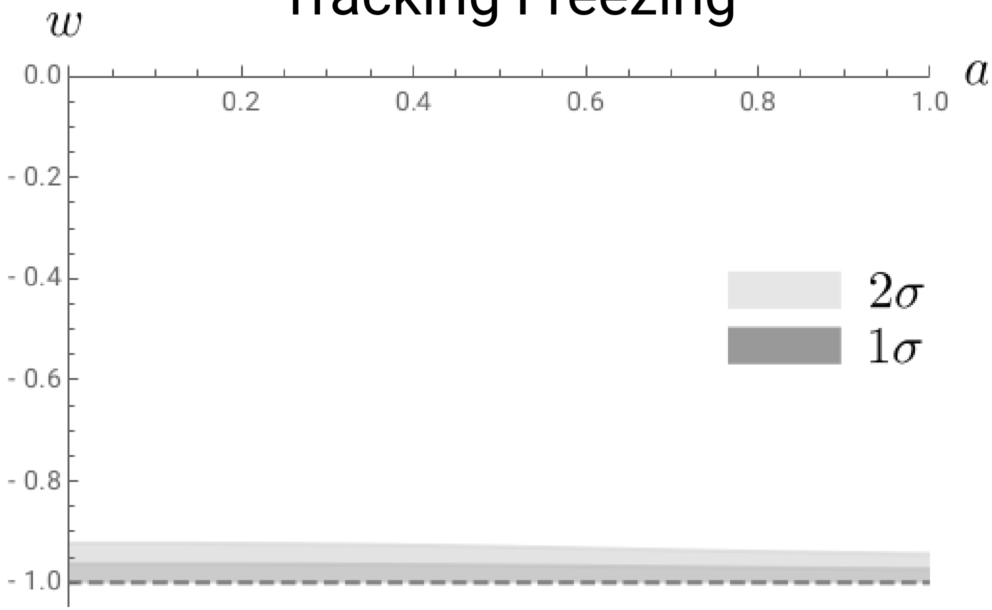
- Constraints: (95% C.L.)

No prior:	With prior:
$0.674 < \Omega_{\phi 0} < 0.719$	$0.670 < \Omega_{\phi 0} < 0.704$
$-1.69 < w_0 < -0.46$	$-1 < w_0 < -0.471$

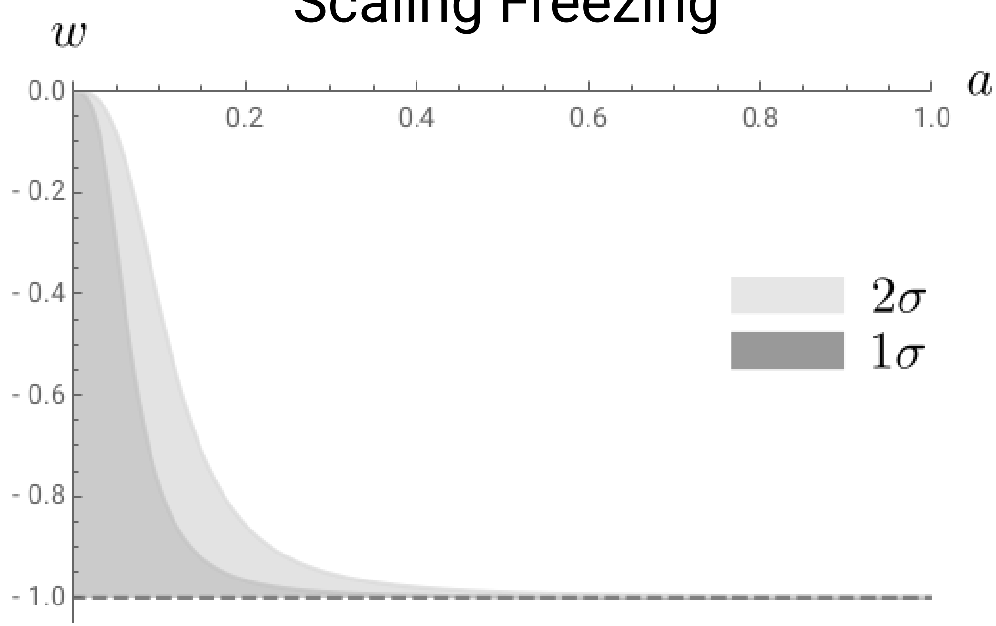
Constraints on quintessence equations of state

(with prior)

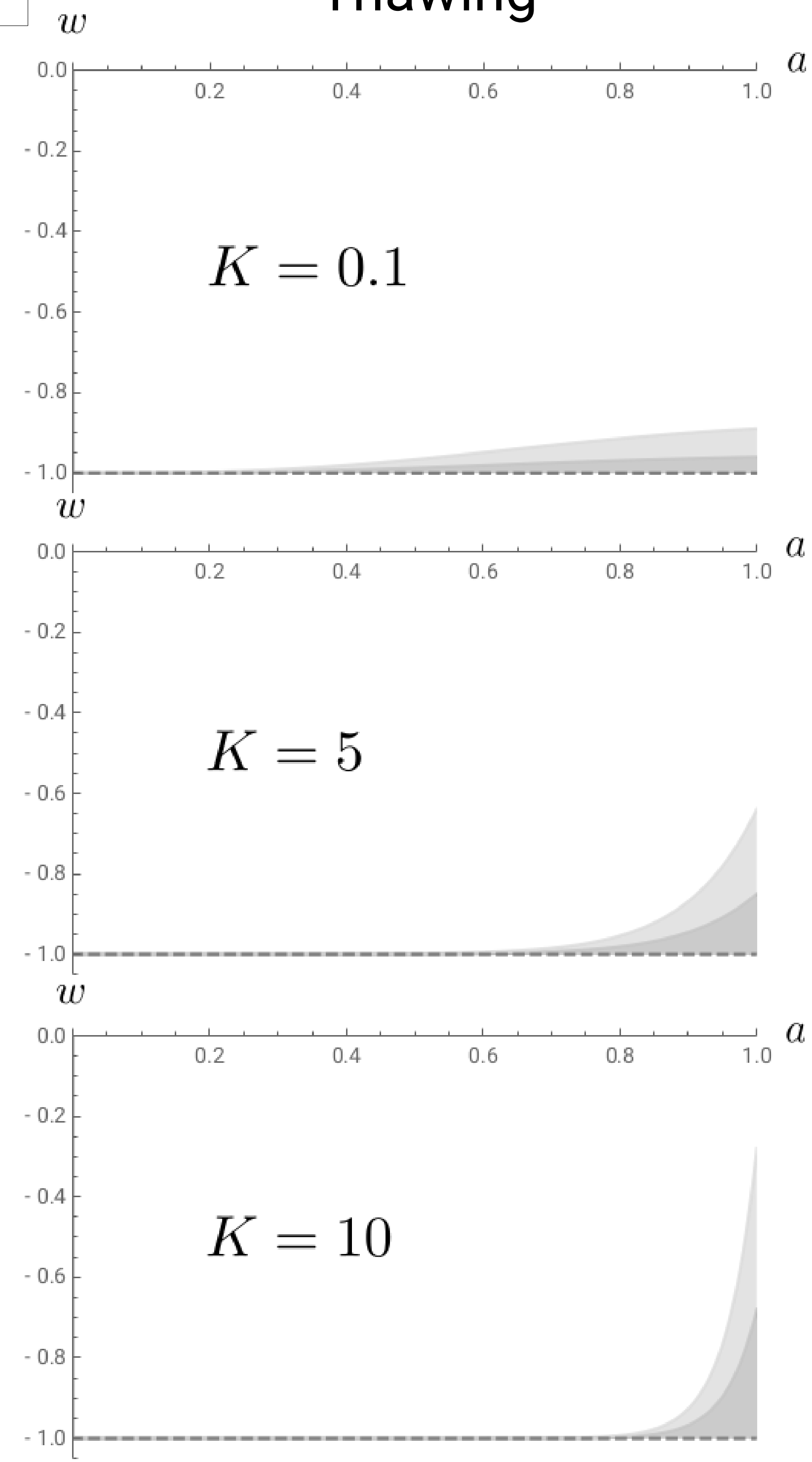
Tracking Freezing



Scaling Freezing

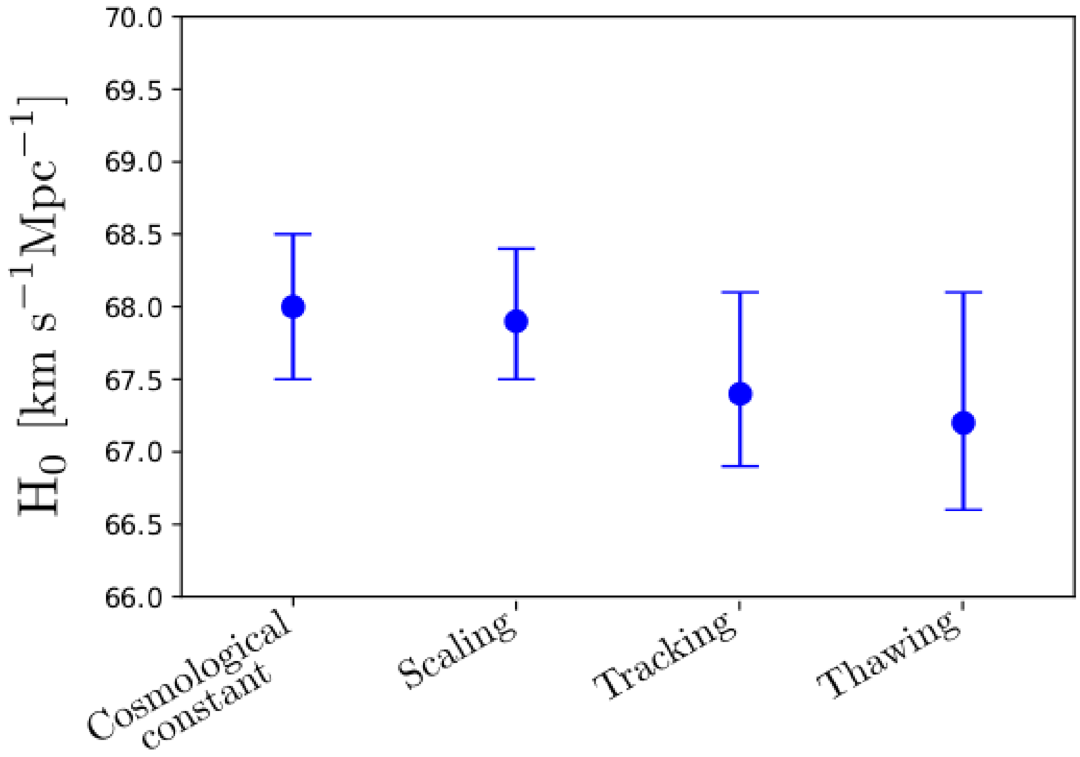


Thawing



Constraints on Hubble constant

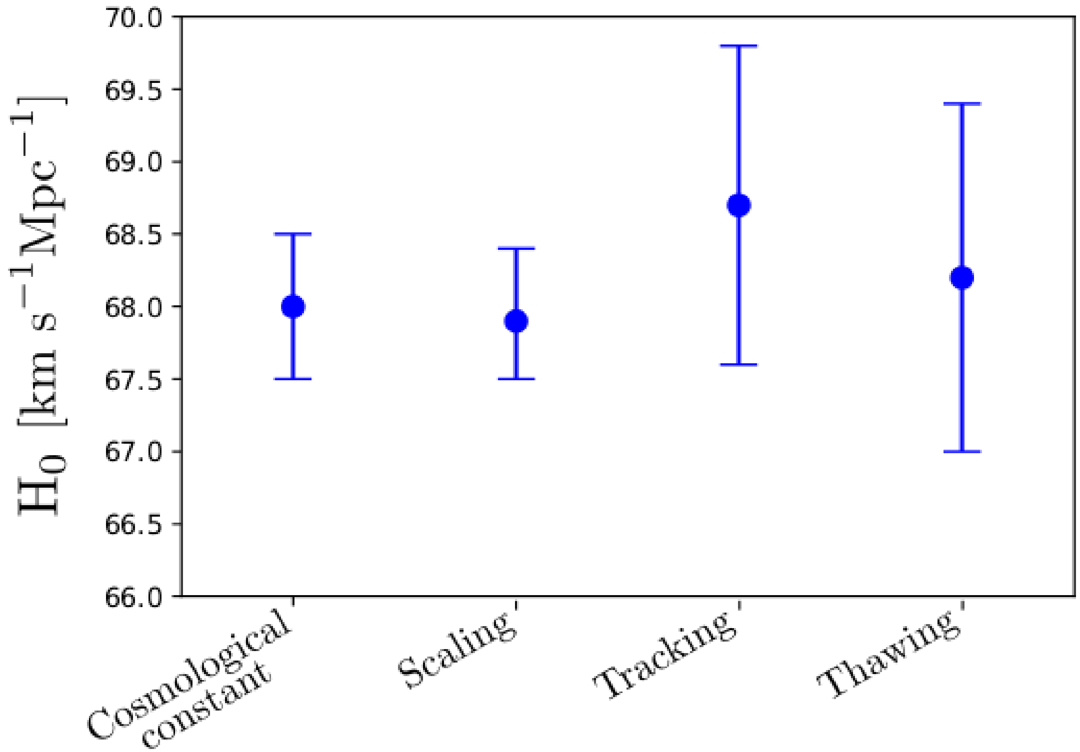
With prior



Does not remedy the tension
between the local measurement and Planck results

Constraints on Hubble constant

Without prior



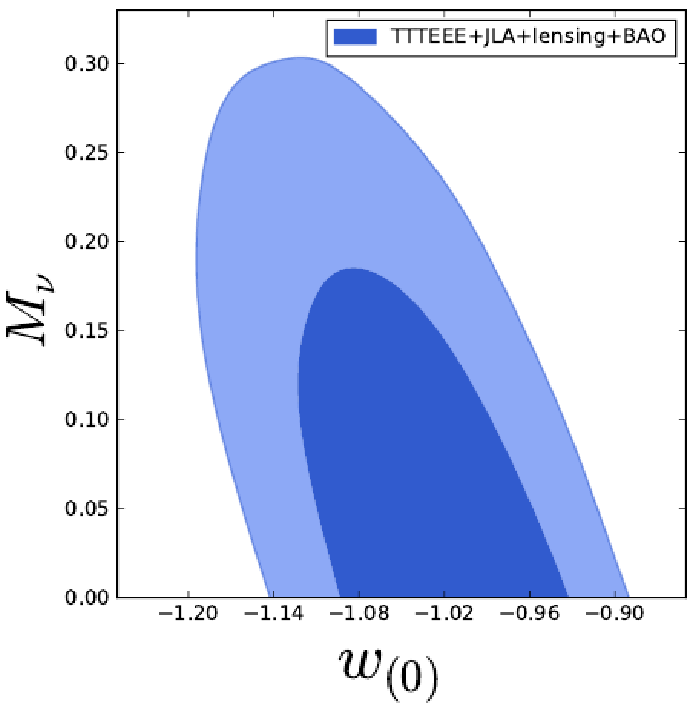
Does not remedy the tension
between the local measurement and Planck results

Constraints on massive neutrinos

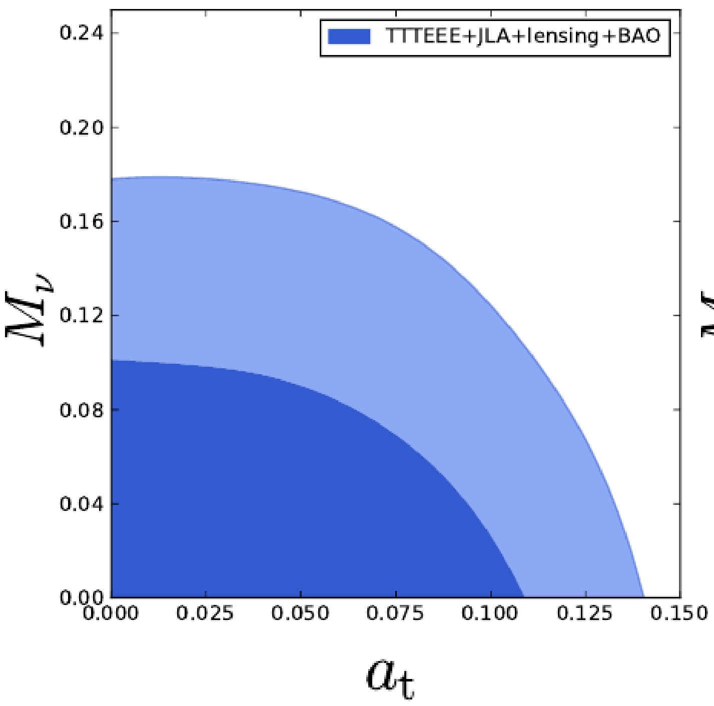
In the above we assumed massless neutrinos.

Considering massive neutrinos (total mass M_ν) we get:

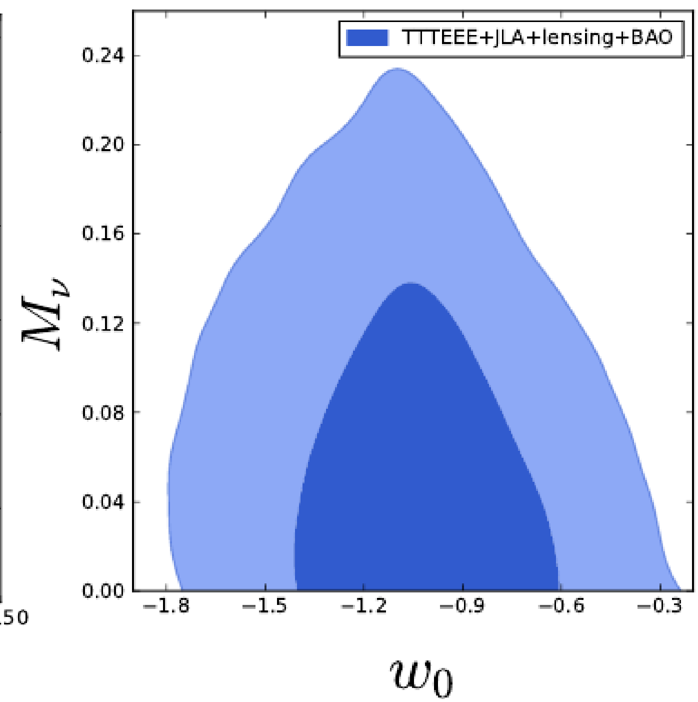
Tracking Freezing



Scaling Freezing



Thawing



- Constraints: $(95\%\ \mathrm{C.L.})$

$M_\nu < 0.25\ \mathrm{eV}$ (no prior)
$M_\nu < 0.15\ \mathrm{eV}$ (with prior)

$M_\nu < 0.16\ \mathrm{eV}$

$M_\nu < 0.17\ \mathrm{eV}$ (no prior)
$M_\nu < 0.15\ \mathrm{eV}$ (with prior)

Thank you for your attention